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Scientific note

Cloudy band observations for annual layer counting on the GRIP and NGRIP, Greenland, deep ice core samples

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***Abstract*:** Cloudy band stratigraphy was observed in the GRIP and NGRIP, Greenland ice cores. Gray value profiles obtained from the photographic recording were analyzed to extract annual layer signals. Simple counting of gray value peaks is effective enough when annual layer thickness is relatively small (smaller than approximately 20 mm), but smoothing of the gray value profile is needed when annual layer thickness is larger. Smoothing can be done by adopting a running mean over a range of half of annual layer thickness estimated from ice flow modeling. A comparison of the DEP profile with the gray value profile revealed that the DEP profile seems to reflect the seasonal variation in general, but not exactly.

key words: cloudy band, gray value, GRIP, NGRIP

1. Introduction

The Greenland and Antarctic ice sheets preserve paleo-climate information. Three deep ice cores have been retrieved from GRIP (72.6°N, 37.6°W (Summit); 1990–1992), GISP2 (72.6°N, 38.5°W; 1990–1993) and NGRIP (75.1°N, 42.3°W; 1996–2001 and continued) in Greenland to depths of 3029 m (Greenland Ice-core Project (GRIP) Members, 1993; Gundestrup *et al.*, 1994), 3053 m (Mayewski *et al.*, 1997) and 3000 m respectively. Cloudy bands are observed in depth zones of colder periods in the Wisconsin glacial ice as alternative layer sequences of cloudy ice and clear ice (Fig. 1). Cloudy ice contains a large amount of small bubbles, which cause light scattering, and the ice looks white (Shimohara, 2000). It has been suggested that cloudy bands are potential indicators of annual layers (Budd *et al.*, 1989). Hammer *et al.* (1978) pointed out that peak dust concentrations occur in visible cloudy bands in ice from the Wisconsin in Camp Century, Greenland core. The spacing between adjacent cloudy ice layers is taken as the annual layer thickness and used for age calculation of the GISP2, Greenland ice core (Meese *et al.*, 1997; Ram and Koenig., 1997). However, counting of cloudy ice layers is not easy due to the complicated structural variations of cloudy ice layers. Quite possibly, each cloudy layer coincides with depositional event of snowfall, which may include yearly trend. Therefore, some kind of data-treatment is needed to extract annual signals from cloudy band features.

One of the simplest methods of data treatment was to extract annual layer signals by tak-

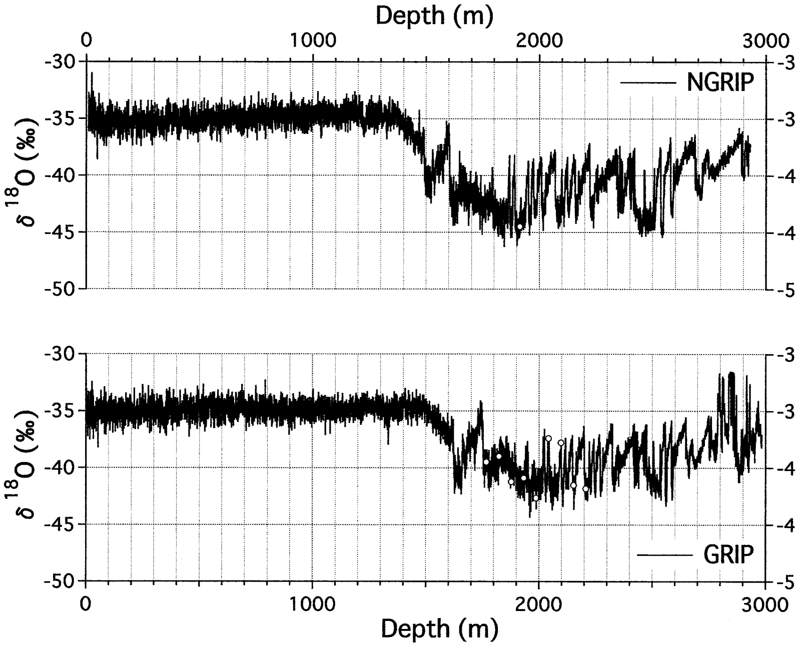

Fig. 1. $\delta^{18}O$ profiles of GRIP and NGRIP ice cores. Open circles show sampling positions for this study.

ing averaged annual layer thickness value at each depth level into account.

2. Experimental methods

Cloudy bands in ice from a greater depth of GRIP, Greenland ice are disturbed due to the complicated ice flow near the bottom (Meese *et al.*, 1997). Ice samples were selected from much shallower depth. Ten slab sections (9 × 55 × 3 cm) in total were cut from the GRIP and NGRIP ice cores as shown in Table 1. Each section length of 55 cm was adopted so as to contain about 10 to 50 annual layer cycles, based on as ice flow calculation for averaged annual layer thickness (ALT_d) along the GRIP ice core (Dansgaard *et al.*, 1993; Dahl-

Table 1. Annual layer thicknesses, calculated (ALT_d) and measured (ALT_s and ALT_r).

Sample NO.	Site	Depth (m)		Annual layer thickness (mm)		
		top	bottom	ALT_d	ALT_s	ALT_r
1	GRIP	1767.15	1767.70	37	16	36
2	GRIP	1822.70	1823.25	37	15	31
3	GRIP	1877.70	1878.25	28	17	27
4	GRIP	1932.15	1932.70	23	17	26
5	GRIP	1987.15	1987.70	15	12	27
6	GRIP	2042.15	2042.70	32	18	37
7	GRIP	2097.15	2097.70	25	20	29
8	GRIP	2152.70	2153.25	14	15	20
9	GRIP	2207.15	2207.70	11	11	18
10	NGRIP	1913.45	1914.00	17	12	23

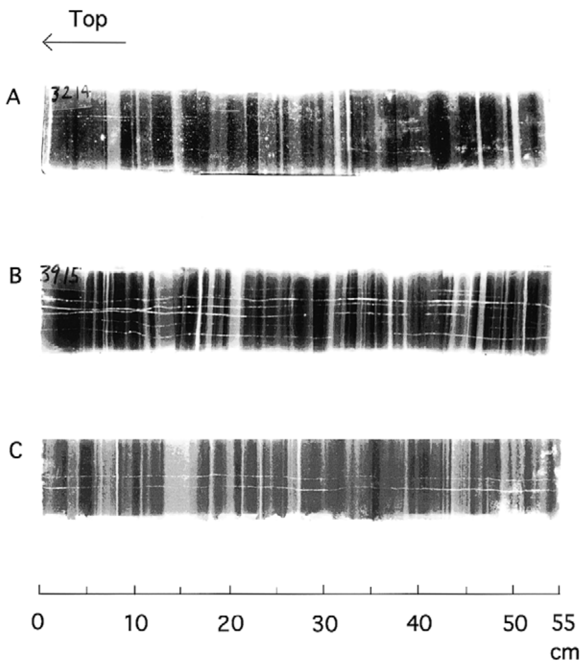

Fig. 2. Cloudy band stratigraphy. A. GRIP sample (Bag No. 3214, Depth 1767.15–1767.70 m), B. GRIP sample (Bag No. 3915, Depth 2152.70–2153.25 m), C. NGRIP sample (Bag No. 3480, Depth 1913.45–1914.00 m) White waved lines along the core axis on the sample surface are scratched traces caused by a probe for ECM measurements.

Jensen *et al.*, 1993). Photographic images of slab sections were recorded immediately after core recovery in the field under side illumination, three examples are shown in Fig. 2. Both distinct and obscure boundaries are observed between cloudy and clear ice layers. Gray value curves were obtained from photographic images of those cloudy band structures. White waved lines along the core axis are scratched traces by ECM (Electric Conductivity Measurement). Gray value profiles were obtained from full width core photographs, minimizing the influence of the scratched lines. Annual layer thickness (ALT_s) was obtained simply by counting gray value peaks along each slab section. The gray value profile was smoothed by adopting running means over a range of half of averaged annual layer thickness (ALT_d) at each depth as shown in Table 1 to emphasize the annual layer signal from the gray value profile. To obtain the ALT_d value at NGRIP, ALT_d of the GRIP core at the same depth was multiplied by the ratio of differences in accumulation rate, a_H between these sites (a_H = 0.23 m/yr at GRIP (Dansgaard *et al.*, 1993); a_H = 0.19 m/yr at NGRIP (Kipfstuhl *et al.*, 2001)).

3. Results and discussion

Gray value profiles obtained from photographic images are shown in Figs. 3 and 4. Gray value increases in cloudy ice layers and decreases in clear ice layers. ALT_s results are shown by open circles in Fig. 5 in which the abscissa shows ALT_d annual layer thickness. If

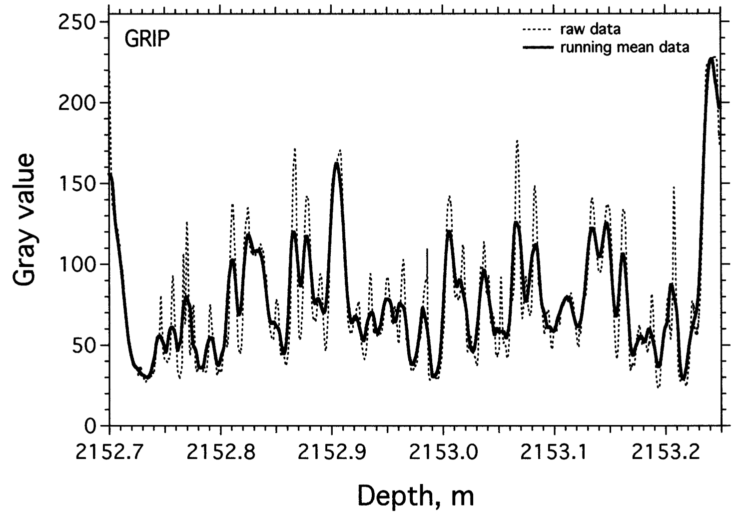

Fig. 3. Gray value profiles of raw data (dotted curve) and running mean data (solid curve) of a GRIP sample from a depth of 2152.70 m.

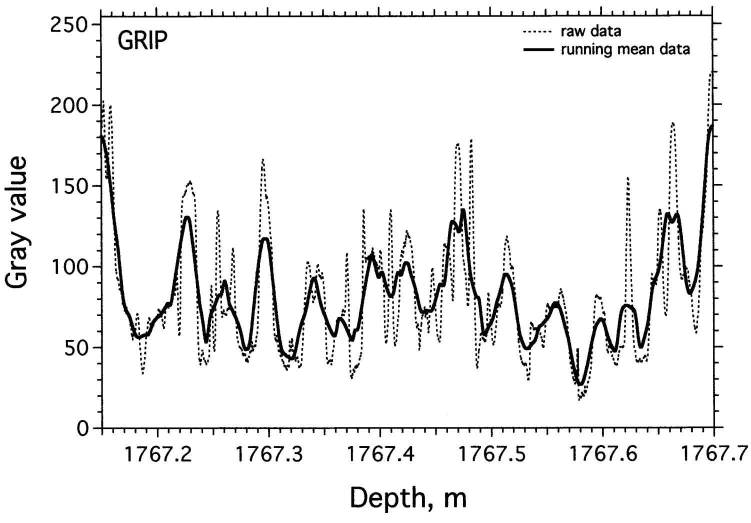

Fig. 4. Gray value profiles of raw data (dotted curve) and running mean data (solid curve) of a GRIP sample from a depth of 1767.15 m.

ALT_s is equal to ALT_d, data points should be on a straight line in Fig. 5. These results show that data points are fairly close to the straight line in a region with ALT_d values lower than about 20 mm, but start to deviate from the line in a larger ALT_d region. This means that multiple cloudy ice layers might correspond to one annual layer.

ALT_r (annual layer thickness from smoothed gray value profile) results are shown by solid circles in Fig. 5 in which data points are much closer to the straight line compared with ALT_s (open circle). This suggests that a pair of cloudy and clear ice layers may not represent

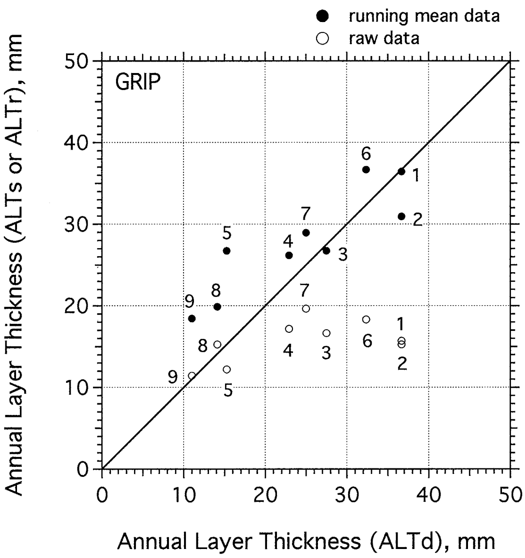

Fig. 5. Measured annual layer thickness (ALT_s or ALT_r) compared with calculated annual layer thickness (ALT_d) by Dansgaard et al. (1993). ALT_s and ALT_r were obtained by simple counting of gray value peaks and by data treatment with running means, respectively. Data points marked by numbers 1 through 9 were obtained with GRIP samples from depths of 1767.15 (1), 1822.70 (2), 1877.70 (3), 1932.15 (4), 1987.15 (5), 2042.15 (6), 2097.15 (7), 2152.70 (8) and 2207.15 (9) m, respectively.

an annual layer, but reflect only precipitation events as expected. However, we may extract annual layer signals from the gray value profile by adopting running means when ALT_d is available.

Simple counting of gray value peaks is effective enough for a lower ALT_d region as mentioned before. A detailed profile of an example is shown in Fig. 3 for a sample from a depth of 2152.70 m at the GRIP site. There is not much difference between raw data and running mean data profiles in Fig. 5, which is also clear from the fact that ALT_s of data number 8 is close to ALT_r of data number 8 in Fig. 5. ALT_r of data number 1 is larger than ALT_s of data point number 1 by a factor of two or more in Fig. 5. Gray value profiles are shown for this sample from a depth of 1767.15 m at the GRIP site in Fig. 4. The two profiles in Fig. 4 are almost identical in some places and quite different in other places, suggesting that a wide range of precipitation patterns have formed the annual layers.

A gray value profile of an NGRIP sample from a depth of 1913.45 m is compared with the DEP (Dielectric Property measurement) profile (Kipfstuhl *et al.*, unpublished data) in Fig. 6. DEP signals were obtained with an apparatus with 5 mm resolution. Therefore, information on seasonal variation in a yearly-length less than 1 cm cannot be detected by DEP. A comparison between gray value profile (running mean data) and DEP profile reveals that DEP profile seems to follow the seasonal variation of gray value in general where the yearly-length is longer than approximately 2 cm, but differs from the seasonal variation at several positions (*e.g.*, at a depth of 1913.48 m). This deviation might be caused because the DEP signal is not controlled by a single component but by four components: ice, acidity, ammonium and sea salt (Wolff *et al.*, 1997). Microscopic observations of cloudy bands

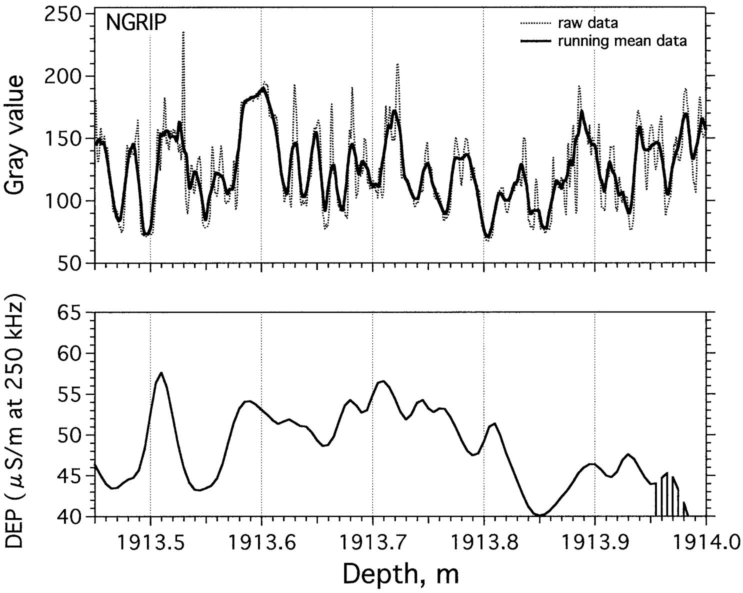

Fig. 6. Gray value profiles of raw data (dotted curve) and running mean data (solid curve) of an NGRIP sample from a depth of 1913.45 m, compared with the DEP profile.

(Shimohara, 2000) reveal that cloudiness resulted from a large number of small air bubbles (micro-bubbles, several microns in diameter). In the formation of these micro-bubbles, dust particles probably play a role in nucleation. This suggests that a cloudy band profile could be proxy data for dust bands in deep ice cores.

4. Conclusions

We tried to extract annual layer signals from cloudy band stratigraphy. The gray value profile of a cloudy band reflects seasonal variation when ALT_d is small, but needs to be smoothed by adopting running means over a range of half of ALT_d when ALT_d is greater than approximately 20 mm.

Acknowledgments

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